Region-specific ground motion relations for the Pacific Northwest

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Non-technical Summary: At present, the national seismic hazard maps in the PNW region rely on ground motion relations developed from data in other regions. The current practice may produce biased ground motion estimates, possibly by as much as a factor of two. It is important to have unbiased estimates of the seismic hazard so that informed engineering design and retrofit decisions can be made. This project utilizes recent high-quality seismographic and strong-motion recordings of moderate-to-large earthquakes in the Pacific Northwest (PNW), including the 1999 Satsop and 2001 Nisqually earthquakes, to develop region-specific ground motion relations for the PNW, including separate ground motion relations for crustal, in-slab and subduction earthquakes.

Introduction

There is growing recognition of the earthquake hazard from both crustal and subduction earthquakes in the Pacific Northwest (PNW) region. A priority task to enable reliable seismic hazard estimation for the region is the development of region-specific ground motion relations, which predict average ground motion amplitudes (response spectra and peak ground acceleration and velocity) as simple functions of earthquake magnitude (moment magnitude, **M**), focal depth, and distance. At present, it is generally assumed that ground motions from shallow crustal events in the PNW may be predicted using empirical ground motion relations developed for California, while ground motions from large subduction events may be predicted based on empirical relations developed from a global subduction database (eg. Frankel et al., 1996, 1999, 2002). These assumptions, born more of necessity than knowledge, do not appear to be well-supported by regional ground motion data. For example, high-frequency ground motions from moderate (**M**5.5) California earthquakes are consistent with an average 'Brune stress parameter' of about 100 bars (Atkinson and Silva, 1997, 2000), while similar studies for moderate shallow Cascadia events report an average stress parameter of 50 bars or less (Atkinson, 1995; Dewberry and Crosson, 1995; Atkinson and Boore, 1997). The **M** 5.1 Duvall, Washington event of 1996 and the **M** 4.3 Georgia Strait event of 1997 are characterized by stress drops of 70 bars and 45 bars, respectively (Atkinson and Cassidy, 1999). This suggests that, on average, California ground motion relations may overestimate the high-frequency motions from shallow crustal earthquakes in the Cascadia region by as much as a factor of two at near-source distances. On the other hand, the attenuation of high-frequency motions from shallow crustal events in Cascadia may be slower than in California, creating a compensating effect.

For the deeper subduction earthquakes, it is standard practice to use empirical ground motion relations developed from a global database (eg. Youngs et al., 1997). The relations most commonly used were developed from a pre-1990 database. Since that time, many more high-quality recordings have become available, from recent earthquakes in Cascadia (eg. 1999 Satsop, 2001 Nisqually), from the KNET strong-motion network in Japan (including a 2001 in-slab event of **M**6.7 that can be directly compared to Nisqually), and from the Guerrero network in Mexico. Clearly, it is important to understand regional differences in ground motion generation and propagation, and differences between crustal, in-slab, and interface events, in order to assess their implications for seismic hazard. The proposed research continues our current efforts to regress, model and understand these differences, for all three types of events, utilizing both regional and global databases.

Progress to Date

An expanded global subduction database has been compiled, containing about 10 times the number of recordings included in the widely-used relations by Youngs et al.(1997). Empirical regression of the expanded global database, using a maximum likelihood technique (Joyner and Boore, 1993), has been conducted and a paper published in Bull. Seism. Soc. Am. (Atkinson and Boore, 2003). The database was published as an electronic supplement to this paper for the use of all researchers. The regressions have revealed some very major differences between the new relations and the previous relations of Youngs et al. (1997). In particular, the new relations demonstrate that the attenuation rates of in-slab and interface events are very different. This can be seen clearly in the data shown on Figure 1, for events in the magnitude range of most interest for hazard analysis (**M** 7 for in-slab events, or **M**≥8 for interface events). The new relations suggest that it is the interface events, rather than the in-slab events, that pose the largest seismic hazard in Cascadia. They also suggest that ground motions recorded in Japan may not be applicable to Cascadia unless regional differences in generic soil profiles (even within the same NEHRP class) can be first accounted for.

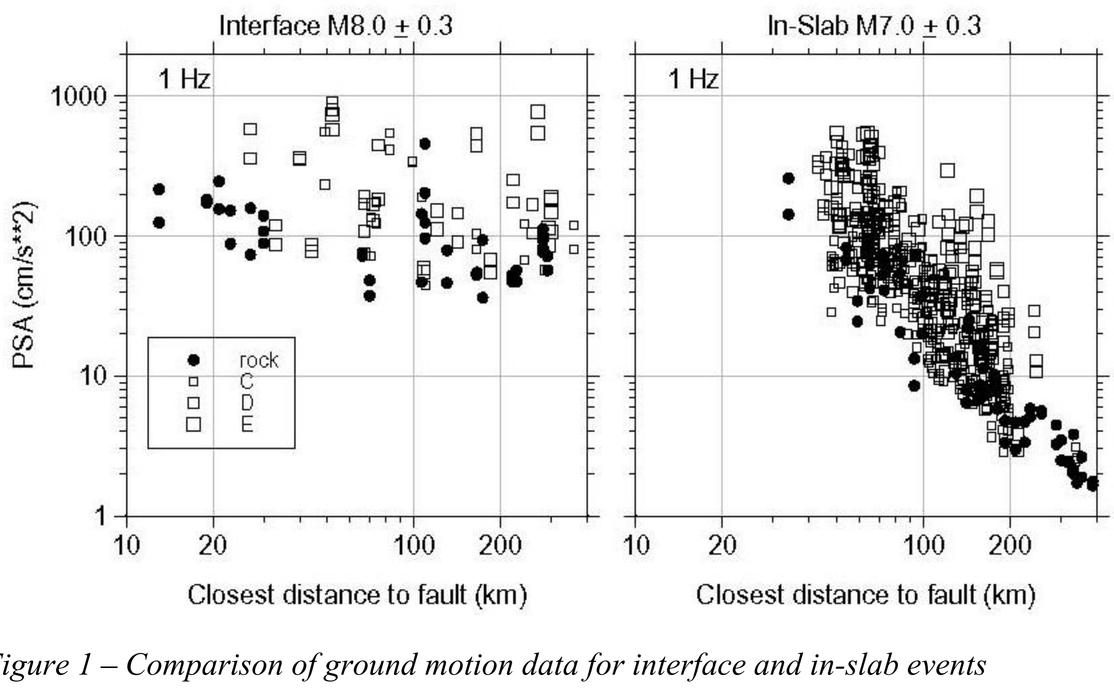

Figure 1 – Comparison of ground motion data for interface and in-slab events

Over the last year, we have compiled and processed seismographic data within the Cascadia region, including crustal and subcrustal events. The database includes all of the 3-component broadband seismographic data for significant PNW events since the mid-1990’s, in addition to selected strong-motion data from significant events. The data are being used to define empirical models of regional propagation and attenuation of crustal and in-slab events, using maximum likelihood regression techniques. This aspect of the study is nearing completion.

With the regional attenuation characteristics defined empirically, regional ground motion relations will be developed using a stochastic finite-fault model. A similar application has just been completed for Puerto Rico (Motazedian and Atkinson, 2003), and the same methodology will be applied in the Pacific Northwest, using the region-specific parameters for that region. Stochastic finite-fault modeling is a valuable tool for interpreting the observed ground motion data, particularly since region-specific attenuation parameters can be readily incorporated. The essence of the method is that a specified fault plane (specified by length, width, orientation in space) is subdivided into a 2D array of subfaults, each of which is small enough to be treated as a point source. The rupture initiates at a specified subfault, and propagates across the fault plane with a specified rupture velocity. The seismic radiation from each of the subfaults is modeled using the stochastic point-source model. The ground motion at a specified site is obtained by summing the contributions from all of the subfaults, lagged in time according to the time of rupture initiation on the subfault and the site-source geometry.

The stochastic finite-fault method has been shown to provide accurate ground motion predictions on average for events of moderate-to-large magnitude, over a wide frequency range (0.2 to 30 Hz), and in a variety of tectonic settings (eg. Schneider et al., 1993; Atkinson and Silva, 1997, 2000; Beresnev and Atkinson, 1997, 1998a,b; 1999, 2001). The accuracy of the finite-fault simulation method is comparable to that of deterministic methods based on more detailed modeling of wave generation and propagation (eg. Somerville et al., 1991), as was demonstrated for the 1985 Michoacan, Mexico earthquake of **M** 8 (Beresnev and Atkinson, 1997) and other events (Hartzell et al., 1999). We will therefore use a finite-fault stochastic model to develop ground-motion relations for Cascadia, for crustal, in-slab and subduction events, including estimates of uncertainty in results due to uncertainty in regional input parameters. The relations will be validated by comparison to the regional ground-motion database.

The resulting ground motion relations will be compared in detail to ground motion observations: 1) specifically for Cascadia; and 2) from the global subduction database. Aleatory uncertainty (eg. random scatter) will be evaluated. In the case of the crustal earthquakes, the relations will be compared not only to the limited Cascadia database, but also to ground motions from shallow crustal earthquakes in both Japan and California.

It is important to study and understand regional differences in ground motion characteristics in order to assess the extent to which data from other regions can be used to fill in the gaps in the sparse PNW ground motion database. This is particularly important to engineers, who often wish to use "real" time histories in nonlinear dynamic analyses of structures; such records are commonly imported from other regions when local records at the desired magnitude and distance are not available. Japan is a particularly fertile region for such comparisons, as it is well-covered by a high-quality strong-motion network with readily available data (KNET), including information on shear-wave velocity at each recording site. Therefore we have made detailed comparisons between Japanese and Cascadia ground motions, for both crustal and in-slab events. A comparison of particular interest is that between the 2001 **M**6.8 Nisqually earthquake in Washington, and a similar **M**6.7 in-slab event that occurred in Japan a few weeks later. Both events had focal depths of about 50 km. Both were well recorded. A paper comparing the ground motions from these events has been published (Atkinson and Casey, 2003). A key finding is that there are significant differences between motions in the two regions even within the same NEHRP site class. This is illustrated in Figure 2. However, if correction factors that account for the difference in typical generic soil profiles in the region are applied, then the observed differences become very small. It is concluded that the observed differences in ground motions between the two regions can be explained by the differences in the depth of the soil profiles of the recording stations; sites in Japan are mostly on shallow soil deposits overlying rock, while sites in the Pacific Northwest are on deeper deposits. There is evidence of significant basin effects that amplify motions in the Puget Sound (Atkinson and Casey, 2003).

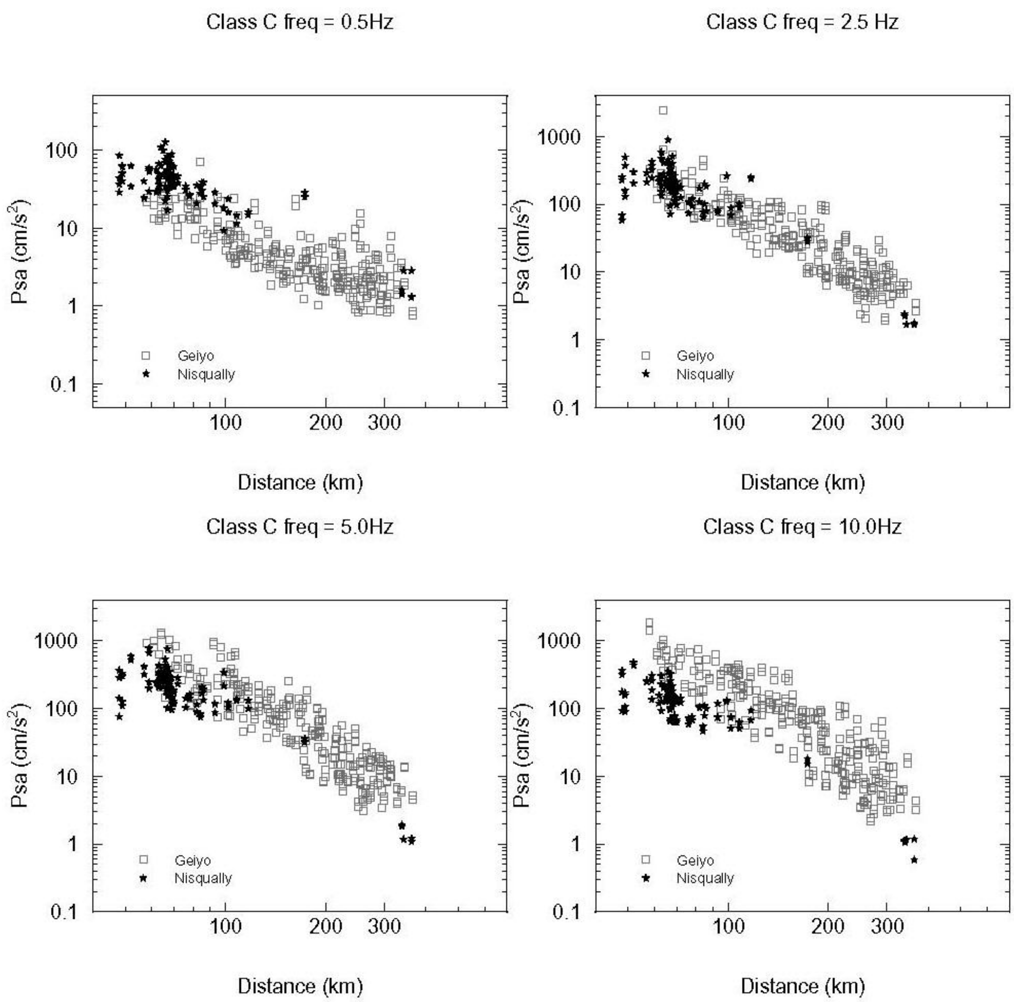

***Figure 2** – Comparison of ground motion amplitudes (5% damped pseudo-acceleration) recorded on Class C sites during **M**6.8 earthquakes in the Pacific Northwest (Nisqually, 2001) and Japan (Geiyo, 2001), at frequencies of 0.5, 2.5, 5 and 10 Hz. Note that Geiyo motions are lower in amplitude than Nisqually motions at low frequencies, but higher at high frequencies (Atkinson and Casey, 2003).*

References

Atkinson, G. (1995). Attenuation and source parameters of earthquakes in the Cascadia region. Bull. Seism. Soc. Am., **85**, 1327-1342.

Atkinson, G., and D. Boore (1997). Stochastic point-source modeling of ground motions in the Cascadia region. Seism. Res. L., **68**, 74-85.

Atkinson, G. and D. Boore (1998). Evaluation of source spectral models for earthquakes in Eastern North America. Bull. Seism. Soc. Am., **88**, 917-934.

Atkinson, G. and D. Boore (2003). Empirical ground-motion relations for subduction zone earthquakes and their application to Cascadia and other regions. Bull. Seism. Soc. Am., **93**, 1703-1729.

Atkinson, G. and R. Casey (2003). A comparison of ground motions from the 2001 M6.8 in-slab earthquakes in Cascadia and Japan. Bull. Seism. Soc. Am., **93**

Atkinson, G. and J. Cassidy (2000). Integrated use of seismograph and strong motion data to determine soil amplification in the Fraser Delta: results from the Duvall and Georgia Strait earthquakes. Bull. Seism. Soc. Am., **90**, 1028-1040..

Atkinson, G. and W. Silva (2000). Stochastic modeling of California ground motions. Bull. Seism. Soc. Am., **90**, 255-274.

Atkinson, G. and W. Silva (1997). Empirical source spectra for California earthquakes. Bull. Seism. Soc. Am., **87**, 97-113.

Beresnev, I. and G. Atkinson (1997). Modeling finite fault radiation from the wn spectrum. Bull. Seism. Soc. Am., **87**, 67-84.

Beresnev, I. and G. Atkinson (1998a). Stochastic finite-fault modeling of ground motions from the 1994 Northridge, California earthquake. I. Validation on rock sites. Bull. Seism. Soc. Am., **88**, 1392-1401.

Beresnev, I. and G. Atkinson (1998b). FINSIM - a FORTRAN program for simulating stochastic acceleration time histories from finite faults. Seism. Res. L., **69**, 27-32.

Beresnev, I. and G. Atkinson (1999). Generic finite-fault model for ground-motion prediction in eastern North America. Bull. Seism. Soc. Am., **89**, 608-625.

Beresnev, I. and G. Atkinson (2001). Source parameters of earthquakes in eastern and western North America based on finite-fault modeling. Bull. Seism. Soc. Am., **91**, in press.

Dewberry, S. and R. Crosson (1995). Source scaling and moment estimation for the Pacific Northwest seismograph network using coda amplitudes. Bull. Seism. Soc. Am., **85**, 1309-1326.

Frankel, A., C. Mueller, T. Barnhard, D. Perkins, E. Leyendecker, N. Dickman, S. Hopper and M. Hopper (1996, 1999, 2002). National seismic hazard maps. U.S.G.S. Open-file Reports.

Hartzell, S., S. Harmsen, A. Frankel and S. Larsen (1999). Calculation of broadband time histories of ground motion: Comparison of methods and validation using strong-ground motion from the 1994 Northridge earthquake. Bull. Seism. Soc. Am., **89**, 1484-1504.

Joyner, W. and D. Boore (1993). Methods for regression analysis of strong motion data. Bull. Seism. Soc. Am., **83**, 469-487.

Motazedian, D. and G. Atkinson (2003). Region-specific ground motion relations for Puerto Rico. Geol. Soc. Am. Special issue on Neotectonics of Puerto Rico, in press.

Schneider, J., W. Silva and C. Stark (1993). Ground motion model for the 1989 M 6.9 Loma Prieta earthquake including effects of source, path and site. Earthquake Spectra, 9, 251-287.

Somerville, P., M. Sen, and B. Cohee (1991). Simulations of strong ground motions recorded during the 1985 Michoacan, Mexico and Valparaiso, Chile, earthquakes. Bull. Seism. Soc. Am., **81**, 1-27.

Youngs, R., S. Chiou, W. Silva and J. Humphrey (1997). Strong ground motion attenuation relationships for subduction zone earthquakes. Seism. Res. L., **68**, 58-73.